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Shock Evolution After Shaped Charge Jet Impact and Its Relevance to Explosive Initiation

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13. ABSTRACT *(Maximum 200 words)*

When a shaped charge jet impacts a target containing explosive, the explosive may be initiated by one of three shocks: the impact shock, a bow shock that forms in the inert plate covering the explosive, or a bow shock that forms in the explosive. In this report, numerical calculations are used to determine how thick the cover plate must be to prevent initiation by the impact shock and how much time (or distance) is required to form a bow shock in the explosive. The results show that the cover plate must be from 4 to 12 jet diameters (depending on jet velocity) thick to sufficiently attenuate the impact shock so that it will not cause initiation in a common secondary explosive. For a 7-km/s copper jet, a distance of about 8 jet diameters was required to form a bow shock in the explosive. This corresponds well to experimental data reported elsewhere.

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1. INTRODUCTION

Shaped charge jets produce enormous shock pressures when they impact a target. The situation is schematically illustrated in Figure 1. These impact shocks attenuate rather rapidly as they propagate into the target. If the jet penetration rate in the target is supersonic, the pressure profile eventually attains the shape shown schematically in Figure 2, where a bow shock is followed by a ramp wave to the stagnation pressure at the jet/target interface. The bow shock is a quasi-steady shock that propagates in front of the jet at the jet penetration rate. It is important that the reader understand the difference between this shock and the impact shock, which is a transient wave that attenuates as it propagates. If the penetration rate in the target is subsonic, the impact shock attenuates to very small amplitudes, and the pressure profile attains the shape shown in Figure 3, which we describe as a ramp wave. Experiments by Chick et al. (1989), and Chick, Bussell, and Frey (to be published) have shown that this leads to at least three distinct mechanisms by which jets can initiate explosives. If the explosive is bare, or if it is protected by a thin cover plate, the impact shock initiates the explosive. In this situation, initiation occurs very close to the impacted surface of the explosive and in a very short time. However, if the cover plate is sufficiently thick, when the impact shock reaches the explosive, it will be sufficiently attenuated that it cannot cause initiation. In this situation, there are two possible mechanisms for initiation. If the penetration rate of the jet in the cover is supersonic, the bow shock which forms in front of the jet in the cover may cause initiation promptly when it enters the explosive (Chick, Bussell, and Frey, to be published). However, if the rate of penetration of the jet in the cover is subsonic, and if the cover is sufficiently thick, the impact shock may evolve into a ramp wave (Figure 3) without an abrupt shock front. Experimental work by Setchell (1981) and theoretical work by Frey (1986) indicate that such a wave is not an effective source of initiation. In this situation, initiation is caused by the bow shock that forms in front of the jet in the explosive. When this bow shock is the initiation source, the distance and time required to achieve detonation are much longer than in the other two cases (Chick, Bussell, and Frey, to be published).

In this report, we use calculations to answer the following questions about this process: (1) How thick must a steel cover plate be to inhibit initiation by the impact shock? (2) How long does it take to form a bow shock in the explosive? Based on this information, we are better able to discuss the experiments reported elsewhere (Chick, Bussell, and Frey, to be published).
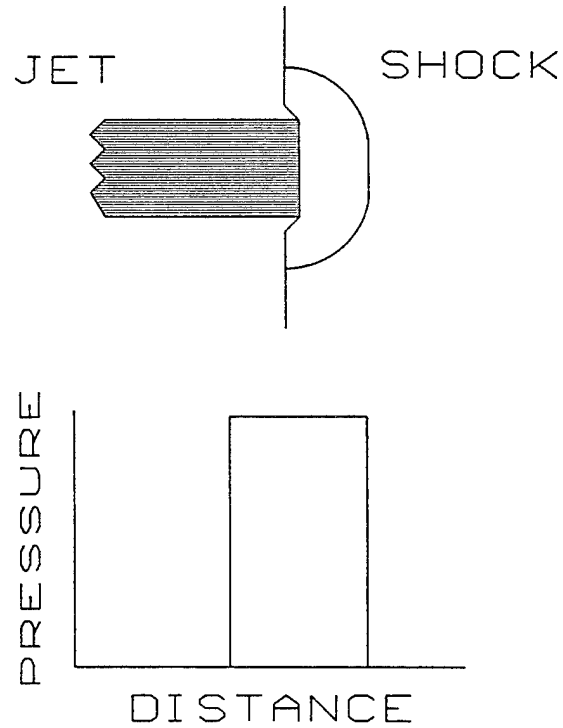
Figure 1. <u>Schematic drawing of an impact shock and the pressure profile on the center line shortly after impact.</u>
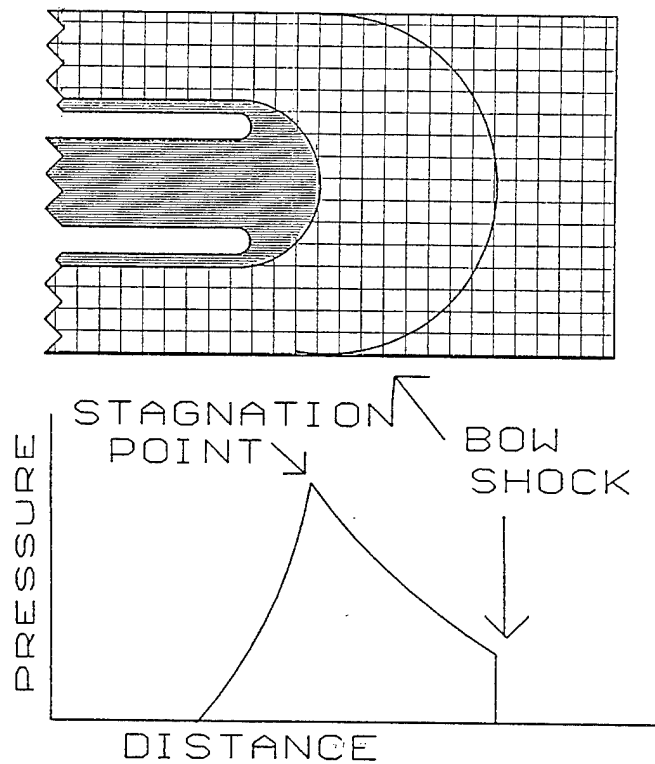

Figure 2. <u>Schematic drawing of a jet penetrating supersonically and the associated pressure profile (on the center line).</u>
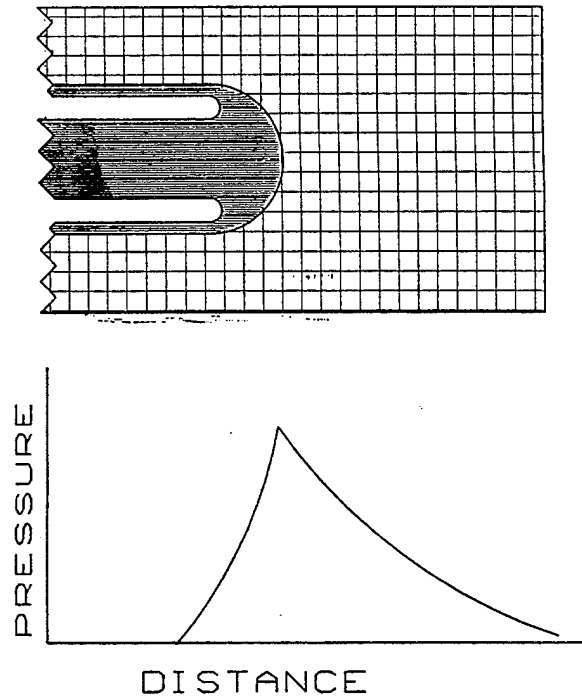
Figure 3. <u>Schematic drawing of a jet penetrating subsonically and the associated pressure profile (on the center line).</u>

2. CALCULATIONS

We calculated what happens when a copper jet penetrates through a steel or aluminum cover plate into nonreactive Composition B explosive (a nonreactive material whose equation of state matches that of solid Composition B). For these calculations, the jet was a constant diameter, flat-faced rod. We used the CTH code that has been described by McGlaun and Thompson (1990). Equations of state, of the Grüneisen form, and constitutive relations were taken from the material library of the CTH code. For steel and aluminum, the constitutive relation was of the Johnson-Cook form. Copper and Composition B were treated as elastic-perfectly plastic. The zone size in the computational mesh was chosen so that there were 48 zones across the diameter of the jet. The calculations were run in such a manner as to keep the jet/target interface fixed at a constant position, so the frame of reference is that of an observer who moves at the jet penetration rate. This was done by having the target move to the right with a velocity equal to the steady-state penetration velocity and the jet move to the left with a velocity equal to the impact velocity minus the penetration velocity.

We will discuss three calculations: (1) a 6-mm-diameter copper jet with a velocity of 7 km/s penetrating a 100-mm-thick steel plate, (2) the same jet with a velocity of 4.5 km/s penetrating a 100-mm-thick steel plate, and (3) a 3-mm-diameter copper jet with a velocity of 7 km/s penetrating a

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50-mm-thick aluminum plate followed by 100 mm of Composition B. As points of reference, we computed the following quantities for each case using analytic relations: (1) the shock pressure at the moment of impact, (2) the bow shock pressure for steady-state penetration, and (3) the stagnation pressure at the jet/target interface for steady-state penetration. The impact and bow shock pressures were computed using Hugoniot parameters taken from Van Thiel, Kusubov, and Mitchell (1966). The impact shock was computed using well-known impedance match methods, and the bow shock was computed assuming that the velocity of the bow shock equals the steady-state penetration rate. The stagnation pressure was computed assuming incompressible hydrodynamic flow. More detail is given in the Appendix. The results are shown in Table 1.

Table 1. Impact Shock Pressure, Bow Shock Pressure, and Stagnation Pressure for the Three Calculations.

Target	Impact Shock Pressure (GPa)	Stagnation Pressure in Cover (GPa)	Stagnation Pressure in Explosive[a] (GPa)	Bow Shock Pressure in Explosive[a] (GPa)
7-km/s Jet Steel	280	51	20	9.6
4.5-km/s Jet Steel	140	21	8.3	1.3
7-km/s Jet Al/Explosive	150	27	20	9.6

[a] Assuming the jet reaches the explosive; it did not do so in all calculations.

NOTE: The bow shock and stagnation pressure are computed for steady-state penetration.

3. RESULTS

Figure 4 shows the pressure in the target as a function of position along the centerline for several times after a 6-mm copper jet impacts a steel target at 7 km/s. Distance in these curves is measured from the jet/target interface, not from the front surface of the target. At impact, the pressure is about 280 GPa, in agreement with the analytic calculation. At the interface, the pressure decays very rapidly. By 2 μs after impact, it has decayed to about 70 GPa. It levels off at about 60 GPa, a little greater than the analytically predicted stagnation pressure, and retains this value for the remainder of the calculation. Shocks can be seen propagating to the left in the steel and to the right in the copper. The shocks continue to decay for some time after impact. After 4 μs, there appears to be a two-wave (two shock) structure in
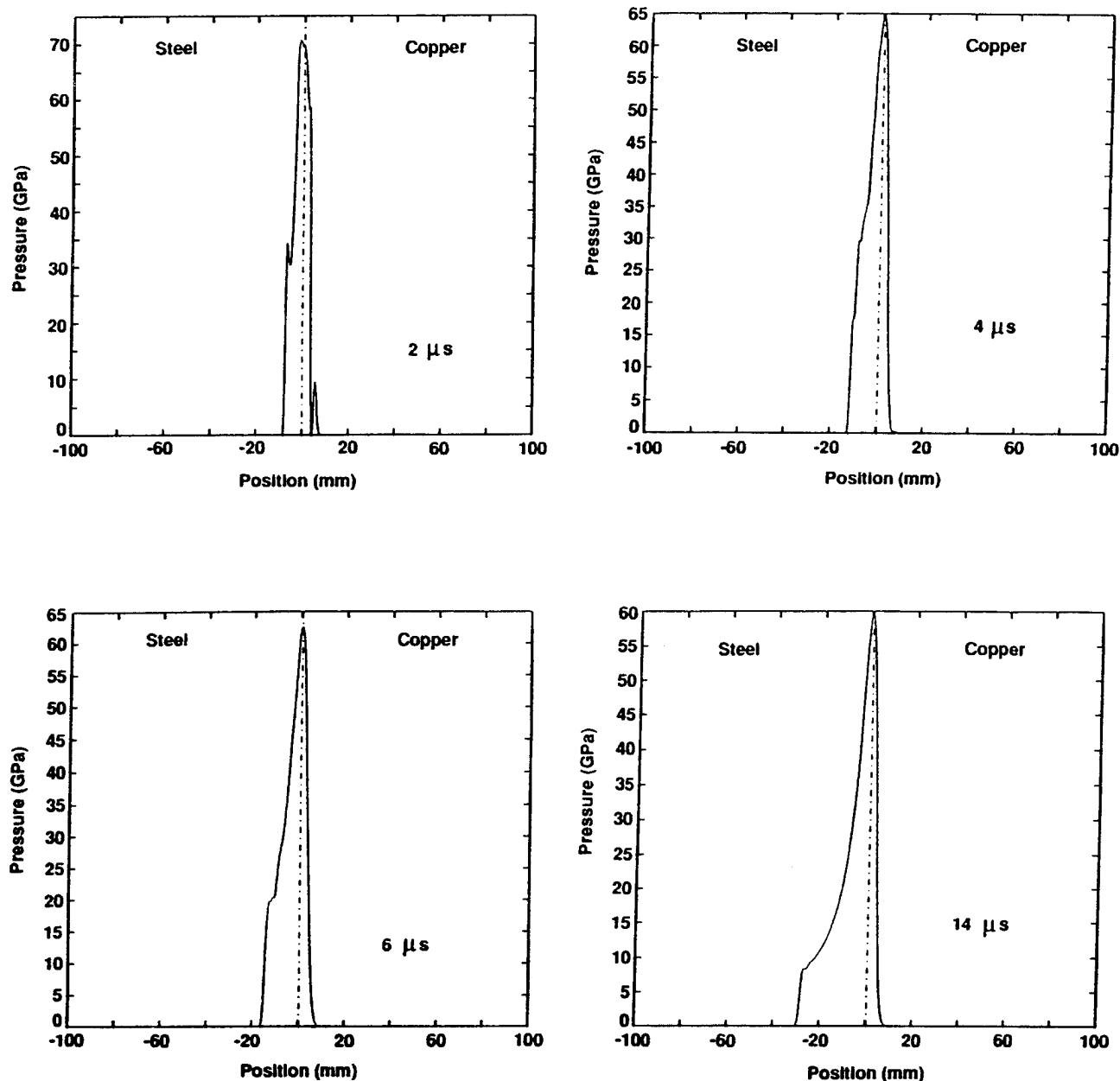
Figure 4. Pressure profiles for several times after impact for the 7-km/s jet hitting a steel target. The origin is moving with the jet/target interface.

the steel. It is tempting to attribute this to the phase transition, which is known in steel at about 130 GPa, but we are not sure that the equation of state used here properly accounts for the phase transition. Calculations of a jet impacting aluminum did not show this double wave structure, so the double shock is apparently related to the properties of the steel. At later times, one would expect to see an elastic precursor in the steel, but the precursor was never apparent in the calculations.

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Figure 5 shows the shock pressure and the jet/target interface pressure as a function of time after the 7.0-km/s jet hits the steel target. As noted above, the interface pressure rapidly decays to its steady-state value. The shock pressure continues to decay for a much longer time. The bump in the shock pressure curve occurs when the second shock (see discussion in last paragraph) overtakes the first.
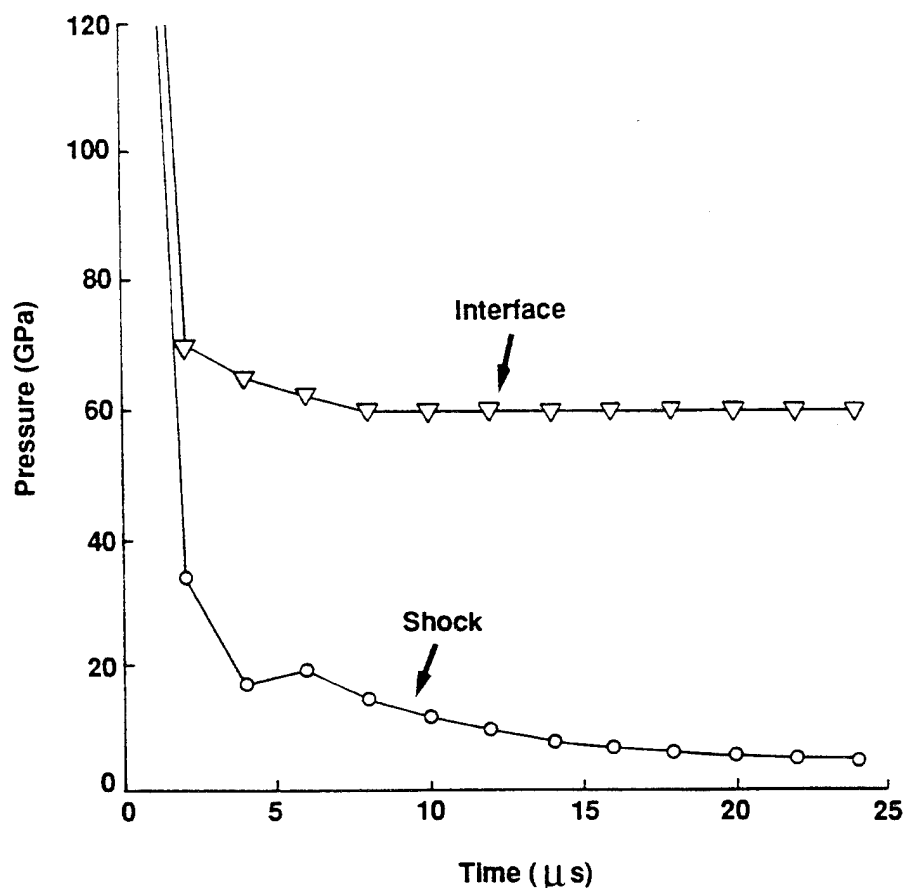
Figure 5. <u>Pressure vs. time at the jet/target interface and at the shock front for the 7-km/s jet impacting the steel target.</u> (The points were obtained from the calculations. The lines are a fit by eye through these points.)

Figure 6 shows the shock pressure vs. distance into the target for the 7.0-km/s jet and the 4.5-km/s jet penetrating a steel target. In this figure, distance is measured from the front surface of the target, not from the jet/target interface. The shock pressure required to initiate Composition B depends upon the duration of the pressure, but Chick, Bussell, and Frey (1988) indicate that a figure of 2.5 GPa is a reasonable estimate in the present circumstances. Impedance match calculations indicate that an 8.0-GPa shock in steel will produce about a 2.5-GPa shock in Composition B. The curves in Figure 6 show that the impact shock from the 4.5-km/s jet would decay to 8 GPa in about 25 mm (4 jet diameters), but the impact shock from the 7.0-km/s jet would require about 75 mm (12 jet diameters) to decay to the same value.
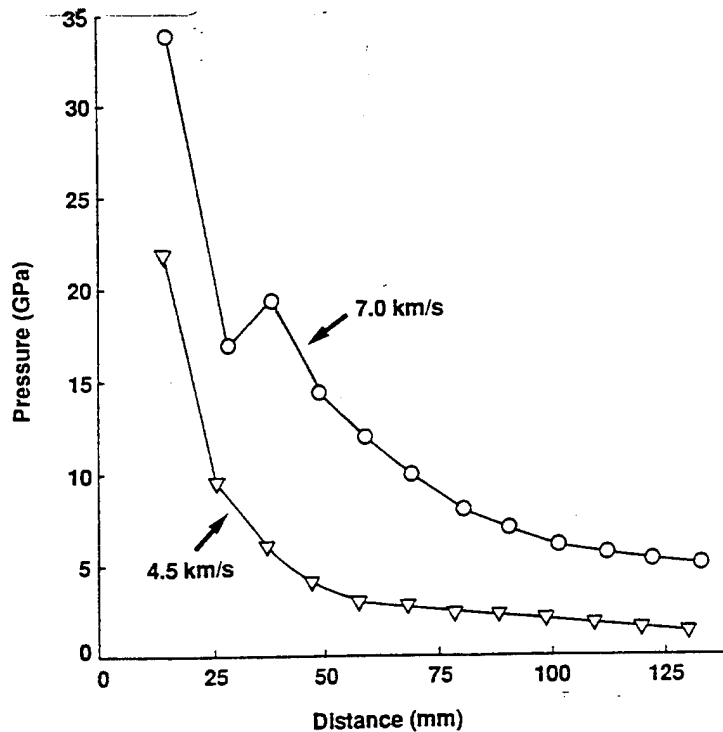
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Figure 6. Pressure vs. distance at the shock front for the 7-km/s jet and the 4.5-km/s jet impacting the steel target. The origin is fixed at the front face of the target.

Figure 7 shows the pressure as a function of position for several times after the jet hits the aluminum/explosive target. The null position in these plots is moving to the left with a velocity equal to the penetration velocity of the jet in aluminum. The vertical dotted line, which moves to the right, is the aluminum/explosive boundary. When the shock enters the explosive, the shock pressure in the explosive is about 2.7 GPa. At a later time, a bow shock forms in front of the penetrating jet, and the shock pressure rises to about 6.3 GPa. This is significantly less than the analytically computed bow shock pressure.

Figure 8 is a plot of the shock pressure vs. distance from the front surface of the aluminum. In the aluminum, the shock attenuates rapidly. After entering the explosive, it remains nearly constant for about 35 mm (6 jet diameters). At this point, the compression from the jet overtakes the shock and strengthens it. The bow shock is well formed at a distance of about 50 mm (8 jet diameters) from the surface of the explosive and has a pressure of about 6.0 GPa (which later increases to about 6.3 GPa). It is important to note that the bow shock in the explosive, when it forms, is stronger than the shock that is transmitted from the cover plate. It is also important to note that the formation of the bow shock requires a considerable distance.

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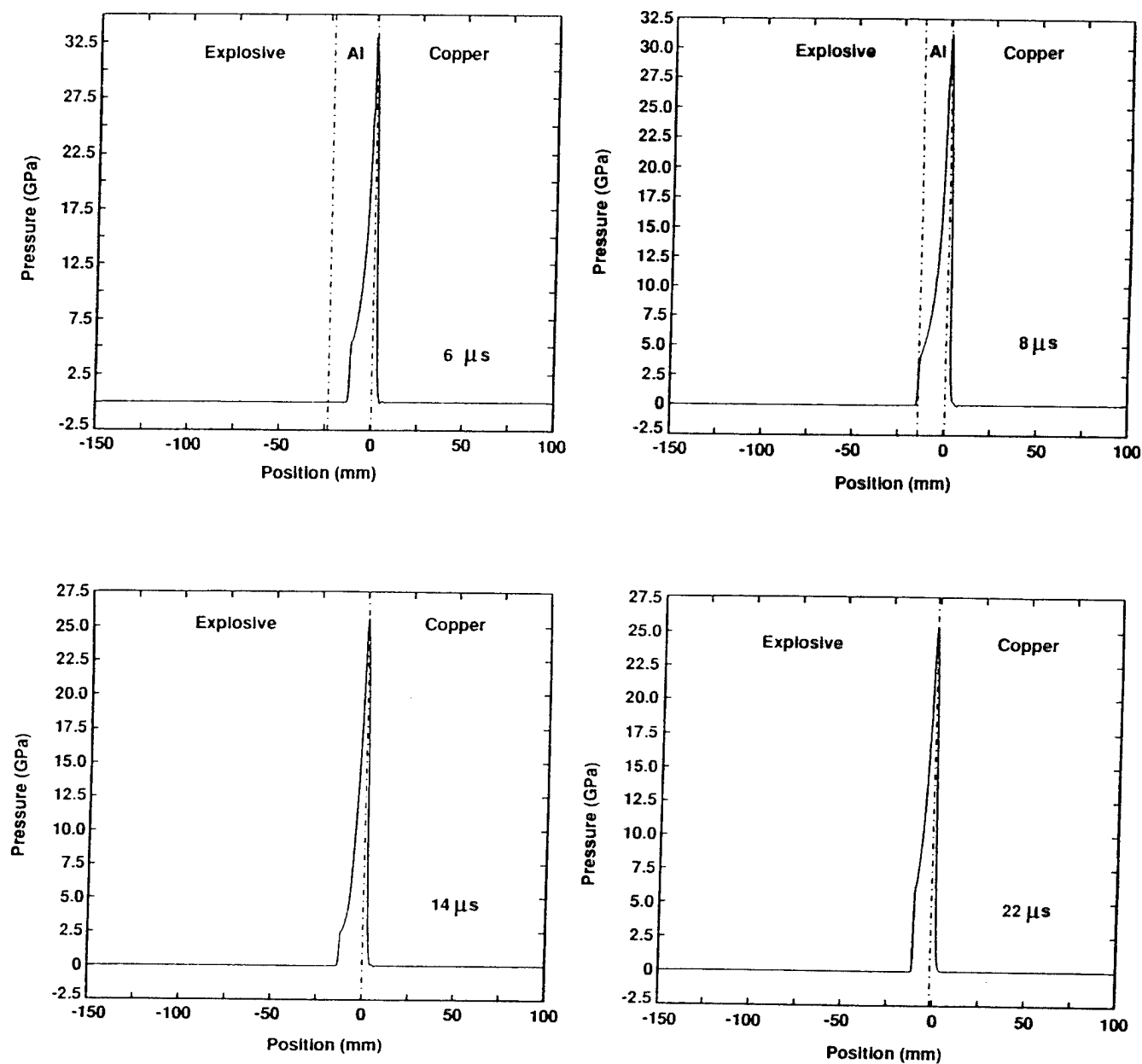Figure 7. <u>Pressure profiles for several times after impact for the 7-km/s jet hitting the aluminum/-explosive target. The origin is moving with the jet/aluminum interface.</u>

4. DISCUSSION AND CONCLUSIONS

Chick, Bussell, and Frey (to be published) reported long run distances to detonation in jet impact experiments with thick cover plates. For a jet with a diameter of about 3 mm and a velocity of about
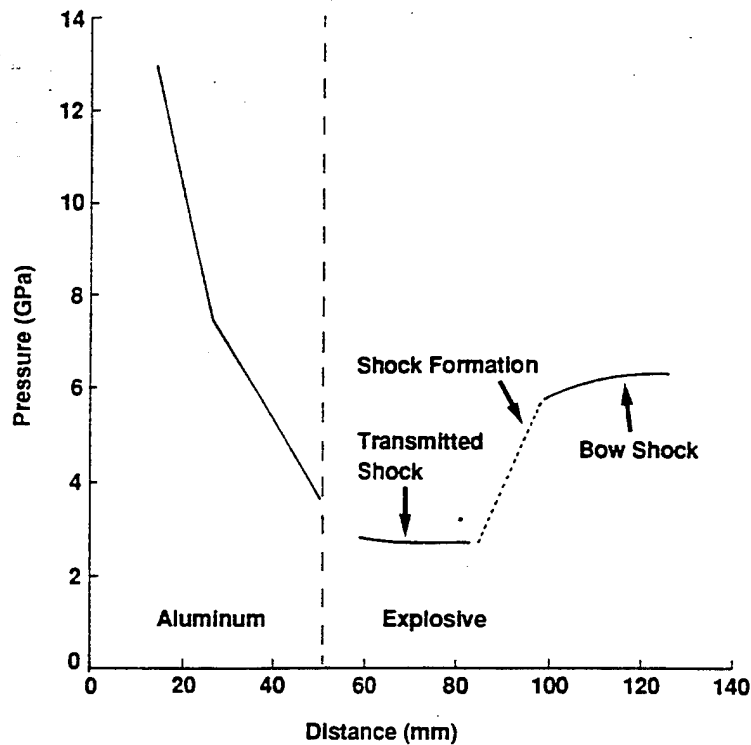
Figure 8. Shock pressure vs. distance for the 7-km/s jet impacting the aluminum/explosive target. The origin is fixed on the front face of the target.

7 km/s, the run distance to detonation was about 25 mm, or just more than 8 jet diameters. This corresponds well with the computed distance to form a bow shock. For a 1.5-mm-diameter jet having a velocity of about 7.0 km/s, the run distance was about 15 mm, or 10 jet diameters. This could be interpreted as a run of about 8 jet diameters to form the bow shock and a distance of about 3 mm for that shock to accelerate to detonation. Thus, the calculations support the hypothesis that the long run distance in the experiments is primarily controlled by the distance required to form the bow shock. Since the explosive sees high pressures well before the formation of the bow shock, the experiments and the calculations provide more evidence for the fact that ramped compression waves are not good sources for initiation, even when peak pressure is obtained in 1 or 2 μs.

The calculations also demonstrate that the distance required to attenuate the impact shock can be quite long (4–12 jet diameters) and depends on jet velocity. The time required to attenuate the impact shock is much longer than the time required to achieve steady-state pressure at the jet/target interface.

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A note about scaling is in order. We assume that, to a good approximation, Hopkinson (U.S. Army Materiel Command 1974) scaling applies to the evolution of the shock wave. Thus, the distance for the impact shock to decay to a given pressure in the cover plate should scale with the jet diameter, and we present this result in terms of jet diameters. The distance to form a bow shock in the explosive depends on both the jet diameter and the cover plate thickness. We have presented this distance in terms of jet diameters, but the reader should be aware that this distance may change as the cover plate thickness changes. The run distance to detonation is, we believe, the distance required to form a bow shock plus the run distance to detonation after the shock forms. The latter quantity clearly does not obey Hopkinson scaling and does not relate in a simple way to the jet diameter. However, one of the points of this report is that the run distance to detonation may be dominated by the distance to form the bow shock. To the extent that this is so, it makes sense to discuss the run distance to detonation in terms of jet diameters.

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APPENDIX:

ANALYTIC PROCEDURES USED TO COMPUTE IMPACT
AND BOW SHOCK PRESSURES

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The analytical procedures used to obtain the results reported in Table 1 are described here. The following nomenclature is used:

U   = shock velocity

u   = particle velocity behind shock

P   = pressure behind shock

V_j = the jet velocity

V_p = the jet penetration rate

γ = the square root of ratio of target density to the jet density

ρ = density.

(In all cases, subscript 1 refers to the jet and subscript 2 refers to the target.)

In these calculations it was assumed that the shock Hugoniots for the relevant materials were linear in u, U space so that

$$U = a + bu. \qquad (A-1)$$

The parameters a and b were taken from Van Thiel, Kusubov, and Mitchell[1] and are given below:

Table A-1. Shock Hugoniot Parameters

Material	a (km/s)	b
Copper	3.92	1.49
Steel	3.64	1.80[a]
Aluminum	5.38	1.34
Composition B	2.71	1.86

[a] Steel has a complicated wave structure. This relation
is good only for particle velocities in excess of 1 km/s.

[1] Van Thiel, M., A. Kusubov, and C. Mitchell. "Compendium of Shock Wave Data." Report UCRL 50108, vol. 1, Lawrence Livermore National Laboratory, Livermore, CA, 1966.

Methods described in Duvall and Fowles[2] were used to compute the strength of the impact shock. Pressure and particle velocity are assumed to be continuous across the jet/target interface just after impact:

$$P_1 = P_2 \tag{A-2}$$

$$u_1 = u_2. \tag{A-3}$$

The pressure behind the impact shock is given by the product of the initial density, the change in particle velocity across the shock, and the shock velocity (i.e., for the target),

$$P_2 = \rho_2 \, u_2 \, U_2 = \rho_2 \, u_2 \, (a_2 + b_2 u_2), \tag{A-4}$$

and for the jet,

$$P_1 = \rho_1 \, (V_j - u_1) \, U_1 = \rho_1 \, (V_j - u_1) \, [a_1 + b_1 \, (V_j - u_1)]. \tag{A-5}$$

The pressure of the impact shock is obtained by solving equations 4 and 5 simultaneously.

The stagnation pressure at the jet/target interface is computed by using the well-known Bernoulli relation:

$$P = 0.5 \, \rho \, V_p^2. \tag{A-6}$$

The strength of the bow shock which forms in front of the penetrating jet in the explosive was computed by assuming that the velocity of the bow shock is equal to the jet penetration rate (i.e., $U = V_p$). This is a good assumption when the jet is penetrating in a quasi-steady-state manner. The penetration rate was computed with the usual formula for incompressible flow:

$$V_p = V_j/(1 + \gamma), \tag{A-7}$$

---

[2] Duvall, G. F., and R. Fowles. "Shock Waves." High Pressure Chemistry and Physics, chap. 9. Edited by R. S. Bradley, London: Academic Press, 1963.

the particle velocity behind the bow shock was obtained from (A-1):

$$u = (U - a)/b, \qquad\qquad (A-8)$$

and the shock pressure was obtained by the relation (A-4) used above:

$$P = \rho\, u\, U. \qquad\qquad (A-9)$$

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